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FIELD GUIDEBOOK TO THE REEFS AND GEOLOGY OF

GRAND CAYMAN ISLAND, B.W.I.

H. H. Roberts

December 1977

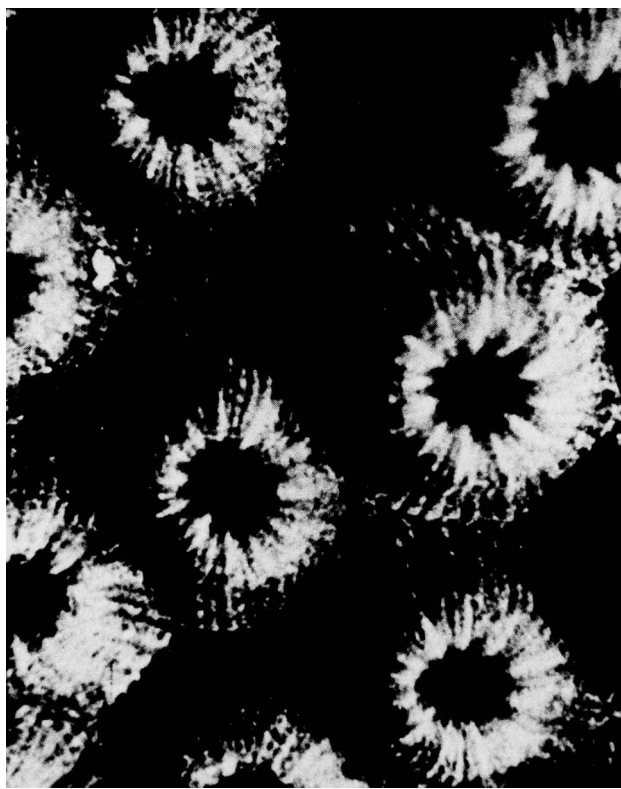
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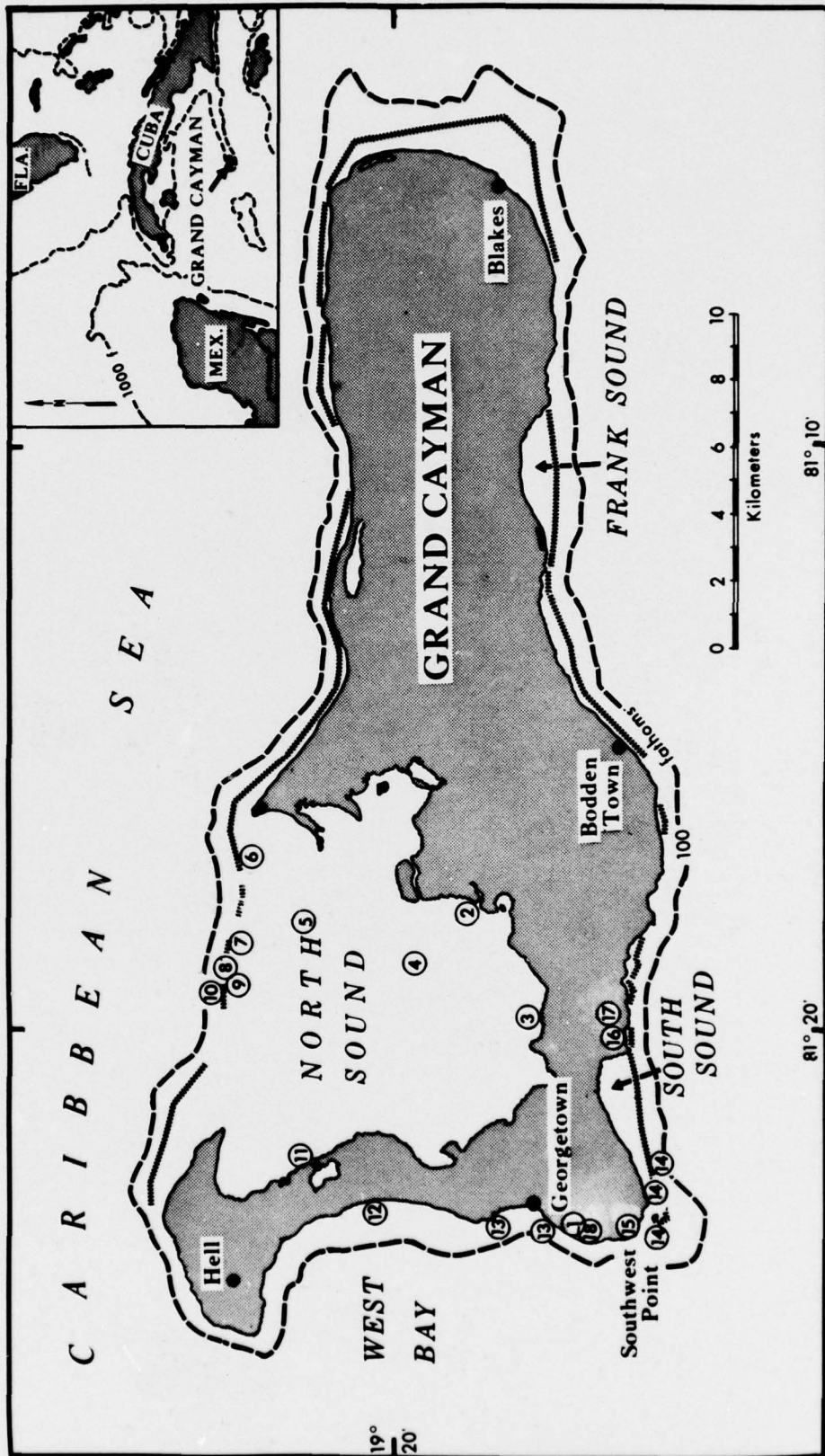
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Third International Symposium
on Coral Reefs, University of
Miami, Fisher Island, Miami
Beach, Florida, May 1977.

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A FIELD GUIDEBOOK TO THE REEFS AND GEOLOGY
OF GRAND CAYMAN ISLAND, B.W.I.

Wednesday, May 18, 1977

- 1:45 p.m. Leave from Miami on Southern Airlines Flight 221, arriving Grand Cayman 3:01.
- 4:30 p.m. Brief orientation at Sea View Hotel and inspection of lee side shelf environments (SCUBA or snorkel).
- 8:30 p.m. Orientation discussion of environments and subjects to be covered during the field trip, plus a stop-by-stop explanation of the field trip schedule.

Thursday, May 19, 1977

Initiation of Environmental Traverse across North Sound and Adjacent Fringing Coral Reef

- STOP 1: Brief orientation lecture on environments and subjects to be covered during the seminar, plus a stop-by-stop explanation of the field trip schedule (Sea View Hotel).
- STOP 2: Fringing red mangrove (Rhizophora mangle) swamp along the southeastern shore of North Sound; a stable peat-forming environment.
- STOP 3: Rocky shore zone near the southern margin of North Sound; a sediment-poor, shallow region with a unique benthic community.
- STOP 4: Vast Thalassia meadows that are the sites of prolific fine-grained calcium carbonate sediment production and high organic productivity in a rather quiescent setting.
- STOP 5: Sand sheet that has spread lagoonward from the fringing reef that separates North Sound from the open sea. Patch reefs and hard grounds in the sand sheet area will also be visited.
- STOP 6: Moat zone near the fringing coral reef and its large Montastrea annularis patch reefs and extensive Acropora cervicornis thickets. The hydrodynamics of this region of the sound will be discussed with reference to growth form adaptations.

Friday, May 20, 1977

Completion of Environmental Traverse across North Sound and Adjacent Fringing Coral Reef and Shallow Windward Shelf, Plus Inspection of Pleistocene Exposures along the Sound's Western Margin

- STOP 7: Rubble flat; a debris plain composed of reef crest coral fragments, localized directly lagoonward of the reef crest.
- STOP 8: Acropora palmata fringing reef crest. Wave and current interactions with the reef crest are stressed; sediment production and growth form adaptations are discussed.
- Stop 9: Acropora cervicornis thickets that have developed in a wave- and current-protected environment. These colonies have assumed very unusual growth forms.
- STOP 10: Shallow fore-reef shelf seaward of the fringing reef across North Sound.
- STOP 11: A Pleistocene tidal channel filled with oolitic accretion beds.

Saturday, May 21, 1977

Deep Fore-Reef and Lee Side Environments

- STOP 12: Sediment-rich lee-side shallow shelf and beach.
- STOP 13: Lee-side patch reefs (Soto's reefs and Eden Rock).
- STOP 14: South Sound sand cay and back-reef Porites patch reefs and/or an optional SCUBA dive on the deep fore-reef buttress zone. Beach rock and boulder accumulations will be examined on South Sound sand cay.

Sunday, May 22, 1977

Subaerial Environments

- STOP 15: Beach rock at South Point.
- STOP 16: South coast boulder ramparts.
- STOP 17: Tertiary Bluff limestones that form the core of the island.
- STOP 18: Ironshore formation and its representative depositional environments (reef crest, lagoon, and beach).
- 3:50 p.m. Leave Grand Cayman for Miami on Southern Airways Flight 224.

THIRD INTERNATIONAL SYMPOSIUM ON CORAL REEFS

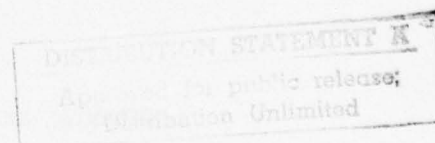
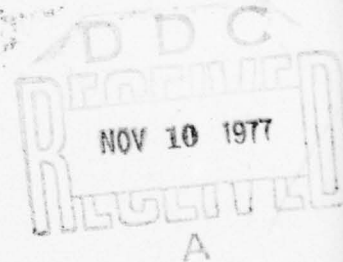
FIELD GUIDEBOOK TO THE REEFS AND
GEOLOGY OF GRAND CAYMAN ISLAND, B.W.I.

BY

HARRY H. ROBERTS
Louisiana State University
Baton Rouge, Louisiana

MAY, 1977

The Atlantic Reef Committee
University of Miami, Fisher Island
Miami Beach, Florida 33139



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Acknowledgment

The major part of the background data which has provided a basis for this guidebook is an outgrowth of several field experiments conducted on Grand Cayman which were funded by the Geography Programs, Office of Naval Research, Arlington, Virginia 22217. Drs. Clyde H. Moore, Jr., and R. L. Folk are gratefully acknowledged for the contribution of several illustrations used in this report, some from published reports and others from recent unpublished research.

INTRODUCTION

The relatively small island of Grand Cayman, located some 240 km south of Cuba and approximately the same distance northwest of Jamaica, is the field seminar study site. Its variety of both Recent and Pleistocene carbonates provides an excellent opportunity for studying a spatially coherent group of carbonate environments that can be examined in a minimum of time and travel. The sedimentary deposits of which Grand Cayman is composed are exclusively carbonates derived from a broad spectrum of environments. These sediments display an extensive array of textures, constituent particles, and diagenetic alterations that are the resultants of combined physical, chemical, and biological processes. Catastrophic events, such as storms and sea level fluctuations, help shape both Recent and Pleistocene sedimentary deposits. A systematic environment-by-environment evaluation of process-product relationships concerning the recent carbonates of Grand Cayman will be followed during the four field days of this seminar (Fig. 1).

REGIONAL GEOLOGIC AND GEOGRAPHIC FRAMEWORK

Grand Cayman, largest of a group of three small islands, is located in the Caribbean Sea approximately 240 km south of the Isle of Pines, Cuba, 288 km northwest of Jamaica, and 725 km east of Yucatan. Its dimensions are approximately 35 km east-west and 6 km to 15 km north-south.

The Cayman Islands are prominences on a submarine ridge, an extension of the east-west trending Sierra Maestra mountain range of southeastern Cuba. The Cayman Ridge is well defined by the 1,000-fathom (1,829 m) isobath, as shown in Fig. 1. Approximately 320 km southwest of the Cayman Islands the Misteriosa Bank occurs as a similar projection on the Cayman Ridge but is not exposed above sea level. Two deep basins border the ridge: the Cayman Trench to the south, with water depths exceeding 3,000 fathoms (5,487 m), and the Yucatan Basin to the northwest, with water depths up to 2,500 fathoms (4,572 m).

During Miocene time the Cayman Islands were apparently part of Jamaica (Butterlin, 1956), forming an area of shallow seas or possibly a land mass. Significant changes in paleogeography resulted from block-faulting during the Pliocene. The Pliocene and Pleistocene faulting seems to have been primarily responsible for the simultaneous development of the Bartlett Trough and the Cayman Islands (Schuchert, 1935). At this time the Cayman Islands were separated from Jamaica and from each other. Uplift of land areas continued into the Pleistocene, as evidenced by elevated shorelines and Pleistocene marine deposits in Haiti and Cuba (Schuchert, 1935). Grand Cayman may have undergone additional uplift at this time; because of its very low relief, it was probably planed by wave erosion in late Tertiary or early Pleistocene times (Doran, 1954).

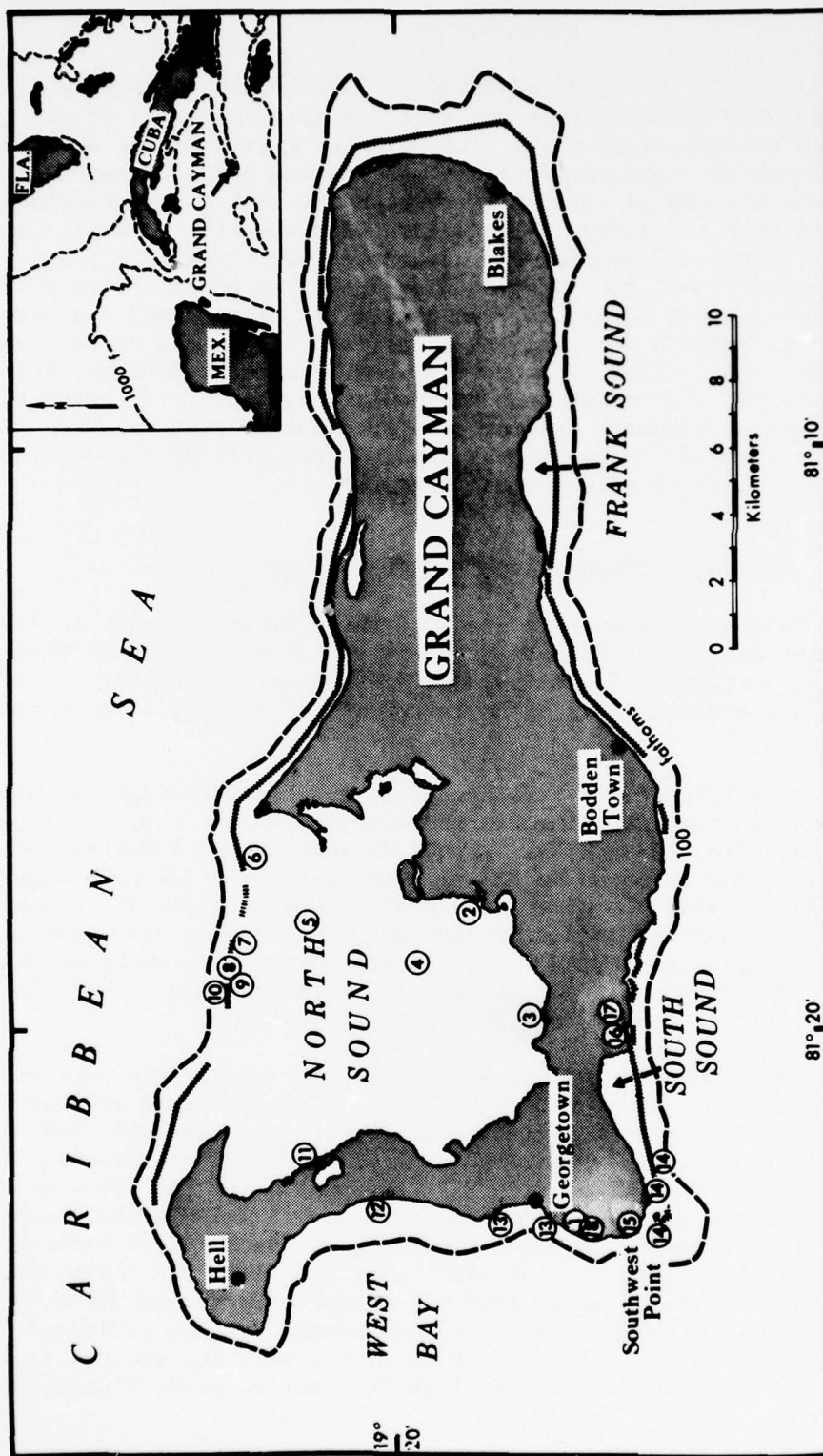


Fig. 1. Location map of Grand Cayman Island showing the areas to be investigated (field trip stops) during the course of the field seminar.

A narrow shelf sculptured by two submarine terraces (approximately 8 and 20 m) is characteristic of the three Cayman Islands. At the shelf margin there is an abrupt break in slope leading to very deep water. Fringing coral reefs and adjacent shallow lagoons are typical of Grand Cayman and Little Cayman but are generally lacking around Cayman Brac. Figure 2 shows a fathometer profile from the south coast of Grand Cayman that illustrates typical shallow- and deep-shelf morphology.

Topographically, the Cayman Islands are relatively flat; average elevations are only a few meters above sea level. In general, the interior of Grand Cayman is very low, the highest relief being slightly over 18 m and occurring on the eastern and northwestern margins. Grand Cayman, like the other two Cayman Islands, is entirely limestone capped. All surface exposures are relatively young and form an emergent platform of Tertiary (?), Pleistocene, and Recent carbonates. Solution of the calcareous bedrock produces a small-scale karst topography whose pinacles, cavities, and other solution phenomena are characteristic surface features of most of the island.

Matley (1926), on a geological reconnaissance of the Cayman Islands, described two limestone formations that compose most of the subaerially exposed portions of all three islands. An older limestone, which forms the central and older part of each island, was called the Bluff limestone. A younger and less lithified formation of both biogenic carbonates and oolites was named the Ironshore formation. This younger limestone occupies most of the island peripheries as a low coastal terrace which never rises to more than 4.5 m above modern mean sea level and generally terminates abruptly inland against raised marine cliffs of the Bluff limestone. In addition to the above formations are recent deposits that surround the islands and consist of fringing reefs, lagoon sediments, beaches, beach rock, storm berms, and boulder ramparts.

The Bluff limestone, which forms the nucleus for Grand Cayman Island, is easily distinguished from more recent carbonates by its very dense, crystalline nature. Coral, molluscan, and foraminiferal skeletal materials were common constituents; however, their remains have been largely removed by solution, and a very distinct moldic porosity has been imparted to the formation. The Bluff limestone forms a rather flat karstland that is generally covered by dense vegetation. The surface is extremely rugged, honeycombed, and traversed by fissures and sinkholes. Bluff limestone fossils from Cayman Brac and Little Cayman have been dated, respectively, as Middle Oligocene and Miocene (Vaughan, 1926). The corresponding limestone of Grand Cayman appears from the coral assemblage to be Miocene in age (Matley, 1926).

The Ironshore formation of Grand Cayman forms an emergent coastal platform of carbonates representative of several depositional environments, including reef, lagoon, oolite bar, and beach. Skeletal remains in this formation are nearly identical to those found in similar modern environments.

PHYSICAL PROCESS SETTING

The interaction of physical processes with coral reefs is complex; each reef system has its own unique set of environmental and morphologic

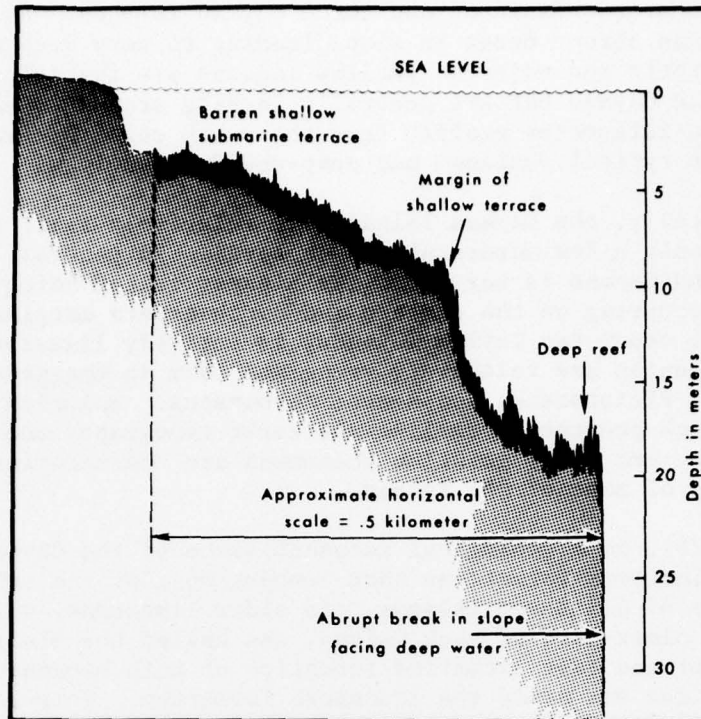


Fig. 2. Fathometer profile taken off the south coast of Grand Cayman Island. The steplike shelf morphology represents two distinct submarine terraces that can be traced around the entire island.

conditions. However, as an approach to understanding these interactions it can be considered that there are regions within tropical latitudes in which a particular combination of physical process variables is operating to produce a common set of response features. The Caribbean area in the vicinity of Grand Cayman Island has a process climate that can be generally characterized by (a) a relatively low amplitude, mixed diurnal and semidiurnal tide regime, (b) a moderately strong unidirectional trade wind and wave field, (c) strong oceanic currents, and (d) a sheltered position with regard to high-latitude storm swell.

Studies of physical processes around islands, in particular Grand Cayman and Barbados, show that the nearshore current field set up by the mean drift past an island plays a large part in controlling large-scale sedimentation patterns. Areas of extensive sediment accumulation on the shelf in turn influence the sites available for reef development (Fig. 3). Unstable substrates provided by most areas of sediment accumulation are not conducive to the initiation and subsequent development of coral reefs. The net circulation around islands has been shown to be important in determining the location and number of zones of high-speed currents or areas of current stagnation. Extensive volumes of sediment generally accumulate to the lee of the high-speed current zones. These

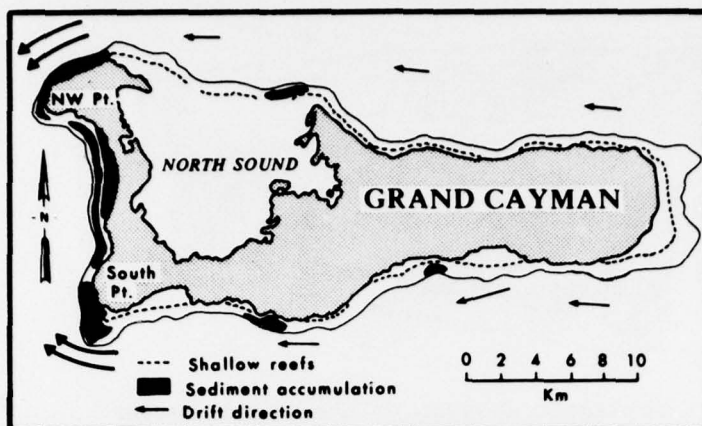


Fig. 3. Distribution of significant areas of sediment accumulation and shallow reef growth as related to a generalized current pattern around the island.

sediments appear to be deposited as the carrying capacity of the current rapidly diminishes when it leaves the high-speed zone. Subsequent reworking of the sediment along the shore is produced by wave and current action. This process of accumulation and redistribution of sediments is common on the lee sides of islands as the strong currents of the island flanks rapidly diminish to the island lee.

Currents on the shelves of steep-sided coral reef islands are controlled both by the mean drift and tides. At the deep margin of these generally narrow shelves tidal currents can be quite strong (in excess of 50 cm/sec along the south coast of Grand Cayman Island, which is in a microtidal environment). These currents are generally directed onshore and may be rapidly attenuated across the shelf because of the frictional drag presented by extremely rough bottom conditions resulting from irregular reef growth. In the Grand Cayman case there is a 60-70% current speed reduction between the shelf edge and the shallow parts of the shelf as a result of these frictional effects. As is schematically illustrated in Fig. 4, currents on the shallow shelf tend to be much weaker and more directionally variable than those near the shelf edge.

The magnitude and directional properties of waves that interface with reefs has a profound influence on gross reef geomorphology as well as growth form adaptations of many members of the reef's organic community. Occurrence of well-developed reefs on windward sides of islands generally confirms the close association between ocean waves and reefs. Morphological elements of the reef such as coral spurs and grooves have been shown to occur in areas around islands or atolls that receive substantial amounts of wave activity. The orientation of these features is affected by the dominant direction of wave approach. In addition to these interactions with the reef, waves can create currents that commonly transport sediment. Waves that break on the shallow reef crest lose about 70% of their energy in the breaking process. After breaking on the reef crest, waves generally continue to break until they are in the lee of the reef crest. At this point they reform into nonbreaking

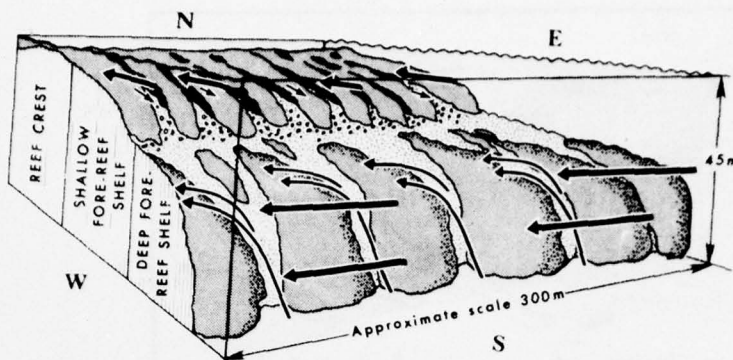


Fig. 4. A schematic diagram of the Grand Cayman fore-reef shelf showing the strong shelf edge currents that are directed onshore through deep shelf margin grooves. Shallow shelf currents are considerably weaker and somewhat more variable with regard to direction.

waves and propagate shoreward with a height and period that are lower than offshore wave conditions. During breaking, however, over-the-reef currents are created that push water as well as sediment into the back-reef lagoon. This process, coupled with the diurnal or semidiurnal pumping action of the tide, is the driving force behind lagoonal circulation in many coral reef settings. Figure 5 illustrates how water transported into a back-reef lagoon by the wave breaking process can set up substantial currents that affect sediment distribution in South Sound, Grand Cayman Island.

Measurements of waves and wave-driven currents have indicated that wave processes at the reef crest are intense and important to the movement of water and sediment in a fringing reef system. Tidal variations in water level on the reef crest cause daily variations in both lagoon wave heights and wave-driven currents.

ENVIRONMENTS AND ORGANIC COMMUNITIES OF NORTH SOUND AND ASSOCIATED FORE-REEF SHELF

This section presents a brief descriptive summary of various environments that are encountered on a north-south traverse across North Sound, the fringing reef, and the adjacent shelf. On such a transect the following environments are recognized and are used as reference in describing the bottom conditions and benthonic communities: mangrove fringing swamp, shore zone, grass plain, restricted lagoon, sand apron, rock ridge, moat rubble flat, reef crest, upper fore-reef, lower fore-reef, and fore-reef slope (Fig. 6).

North Sound is the largest enclosed water body (approximately 10 km in diameter) associated with Grand Cayman Island. The sound is a shallow, dish-shaped basin with water depths rarely exceeding 5 m. Mangrove swamps are encountered around most of the sound's periphery with the

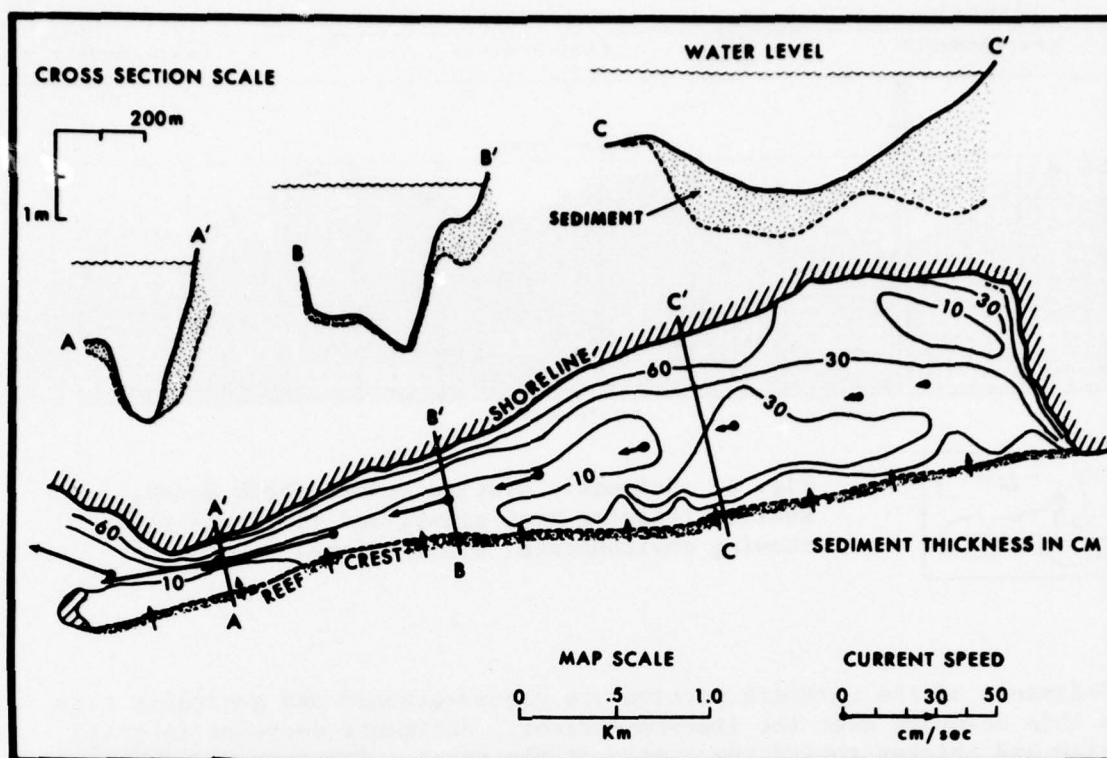
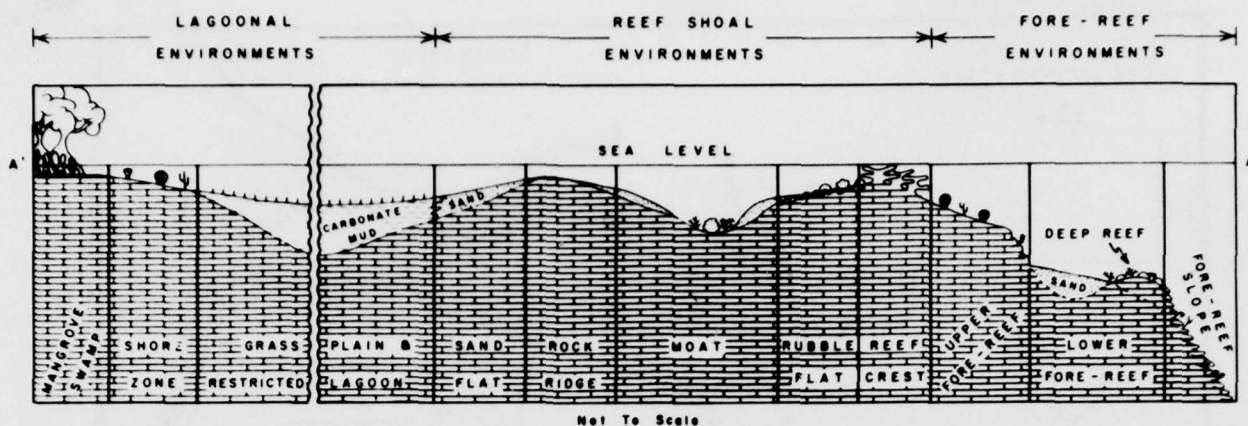


Fig. 5. Sediment thickness in South Sound, in plan view and cross section, shown in relationship to lagoonal circulation produced by wave-driven currents over the reef crest. The lagoonal axis current speed is shown by arrows. Note the correspondence of the thick sediment accumulations and low current speeds and thin sediment cover and high current speeds.

exception of the northwestern and extreme northeastern margins. The northwestern shoreline is formed by a limestone cliff rising up to 4 m above the adjacent lagoon floor. This exposure represents several facies of the Ironshore formation that account for most of the surface limestone exposures on the lee side of the island. The northeastern shore of the sound is a prograding carbonate sand beach system. Fine-grained sediments progressively replace sand southward. A northwest-southeast trending coral reef forms a barrier between the sound and the open sea. Three breaks in the reef serve as the main points of entry for ocean water into the sound. Tidal activity, as well as wind stress from a predominant east-northeast direction, controls general circulation within the sound. Shifts in wind direction and speed, however, can drastically alter normal water movement within this shallow basin.

The floor of the sound, where exposed or examined through a thin veneer of sediments, was found to be limestone similar to subaerially exposed portions of the Ironshore formation. With exceptions of areas along the western and southern shorelines and limited areas near the fringing reef, the sound's limestone substratum is sediment covered.



6. Schematic profile across North Sound, shallow fringing reef crest, and fore-reef shelf showing environmental subdivisions.

Sediments of the northern portion are coarse-grained and generally form a thin covering over the limestone floor. Sediments decrease in grain size and thicken toward the center of the sound. The size and composition of the sediments are variable; however, they all are biogenic. Sediments range from cobble- and sand-sized material near the reef to lime muds in the central and southern regions of the sound.

Fringing Mangrove Swamps

The western, southern, and part of the southwestern margins of North Sound consist of subtidal areas inhabited primarily by mangrove trees. These trees are among the few emergent land plants that tolerate open-sea salinities. Although the three commonest mangrove of the Caribbean--Avicennia nitida (black mangrove), Laguncularia sp. (white mangrove), and Rhizophora mangle (red mangrove)--occur on Grand Cayman, Rhizophora mangle is dominant at the shorelines of North Sound. Avicennia nitida is most tolerant of the hypersaline conditions that sometimes exist at the landward extremities of the swamps and therefore is dominant in those zones. Laguncularia sp. occupies some intermediate position; however, its ecologic limits and distribution patterns are not clear.

Red mangrove is easily distinguished by its large number of prop roots, which serve to support the tree and carry nutrients (Fig. 7). These trees generally grow in very shallow water. Red mangroves normally grow on soft sediment, but occasionally they can be found growing on rock surfaces. Below the sediment surface, thick roots, on which many fine root hairs are attached, may penetrate as deep as 4 m into underlying sediments. The method of rooting and high productivity of the red mangrove makes it an important organic sediment (peat) producer. In addition to efficiently producing peat, the prop root systems provide a dense baffle that is highly effective in reducing current strength and trapping sediment. It has been established that lagoon margins, such as



Fig. 7. Prop roots of the red mangrove, Rhizophora mangle, which stabilize the sediment and in some settings create extensive deposits of peat.

those of North Sound, accrete by this process. Much the same mechanism has been described many times in carbonate literature for the marine vascular plant Thalassia testudinum (turtle grass). In addition, the colonization of soft muds by mangrove seedlings has been known to actually create a new island.

The baffled conditions created by the thick mass of red mangrove prop roots provide numerous habitats for other plants and animals. Sediment-producing calcareous green algae, Halimeda and Penicillus, readily colonize red mangrove areas adjacent to North Sound.

Geologically, mangrove environments are important as areas of organic sediment (peat) production and accumulation. In addition, the baffling and stabilizing effects of the extensive red mangrove prop root systems tend to (a) reduce tidal currents, (b) aid in extensive deposition of predominantly fine grained sediments, (c) by sediment accumulation help create new land, and (d) protect coasts from excessive erosion during tropical storms.

Shore Zone

Along the western and southern margins of North Sound there exists a zone several hundred meters wide in which the sediment cover is reduced to a thin veneer over the lagoon's limestone floor (Fig. 8). Organisms preferring solid substrates have colonized this; they offer a marked contrast to the communities of the grass plain. Alcyonarians, logger-head sponges, and small coral colonies--Porites divaricata, P. furcata, and Siderastrea radians--are common members of the organic community. The calcareous red alga Goniolithon strictum is concentrated locally.



Fig. 8. A thin growth of Thalassia, plus many varieties of calcareous green algae, inhabits the shore zone environment, which has a thin veneer of sediment over a limestone substrate.

A wide variety of brown and green algae cover the bottom. The brown algae, of which Padina and Turbinaria are very common, are relatively restricted to the rocky floor areas. Calcareous green algae are also abundant throughout the shore zone. In areas where the sediment cover thickens, forms anchored in the sediment by basal masses of rhizoids increase in abundance. Halimeda, Avrainvillea, Penicillus, and Rhipocephalus are algae of this variety. Other green algae are present and abundant in the shore zone.

Burrowing bivalves are limited in the shore zone as a consequence of the shallow sediment cover. Gastropods, Foraminifera, and others exhibit similar occurrences, both in kind and number, to those on the grass plain.

Grass Plain

This subdivision of the broad lagoonal environment accounts for approximately 60% of the total area of North Sound (Fig. 9). Most of the hummocky, Callianassa- and/or Arenicola-mounded bottom supports a lush growth of turtle grass, Thalassia testudinum, for which the environment is named, and an abundance of calcareous green algae. Thalassia forms a stabilizing cover for the relatively thick accumulation of sediments (Fig. 10). Green algae are second in abundance to Thalassia. Various species of the genera Halimeda, Penicillus, and Rhipocephalus were the most frequently observed varieties. Other forms, Acetabularia and Avrainvillea, are less abundant and tend to concentrate in localized



Fig. 9. Thick Thalassia growth with numerous conical Callianassa mounds and an abundant infauna of bivalves is characteristic of the grass plain environment. Note the heavily encrusted leaves of Thalassia; these particles contribute to the fine-grained sediment fraction of North Sound.



Fig. 10. Blowouts in the Thalassia beds frequently expose the thick and lengthy root systems of this productive marine plant.

areas. Although some areas appear to have a sparse calcareous green algae population, Stockman et al. (1967) point out that their life cycles are so short that a small population is capable of producing a significant quantity of fine-grained sediment.

Holothurians, short-spined echinoids, various gastropods, and the unattached coral Porites divaricata find the grass plain a suitable habitat. The turtle grass functions as a substrate for small encrusting sponges, Bryozoa, and Foraminifera. Judging from the bivalves scattered over the bottom, a rather abundant infauna must reside in the soft muds. Chione, Codakia, Glycymeris, Laevicardium, and Pinna are the most abundant genera.

Benthonic Foraminifera contribute significantly to the sediments of the grass plain. Miliolids and peneroplids are the most numerous; however, a rather large spectrum of genera is present.

Turtle grass of the lagoon thins to the north, where lime muds merge with sands of the reef-shoal environment. The western and southern boundaries of the grass plain are transitional; a narrow shore zone offers little sediment in which the turtle grass may take root.

Restricted Lagoon

Little Sound constitutes a restricted area of the lagoon environment. It is a natural division in the sedimentary basin because of its isolation from the main current patterns in the major portion of the lagoon, its slightly different organic community, and its highly organic, fine-grained sediments.

Thalassia testudinum is the most characteristic member of the restricted lagoon's organic community. As in the grass plain, the bottom is dotted with sediment mounds formed by burrowing marine organisms. Calcareous green algae and other organisms typically found in the grass plain can usually be noted in the restricted lagoon.

Sand Flat

Shoreward of the rock floor belt is a sizable coralgall sand apron in the northern and northeastern areas of the sound (Figs. 11 and 12). The sand is composed primarily of skeletal debris resulting from biological and mechanical destruction of the reef community. In localized areas within the sand flat nonbiogenic grains may be concentrated. Aggregate grains resulting from recent submarine cementation, for example, occur locally in association with main passages through the fringing coral reef.

Green algae are the most predominant members of the sand flat community. Penicillus and Halimeda account for the bulk of green algae present. Rhipocephalus, Udotea, and Acetabularia are less populous forms. A sparse growth of the turtle grass, Thalassia testudinum, is interspersed with the green algae. The large gastropod Strombus gigas is present throughout the sand flat, and starfish are rather abundant in localized areas.



Fig. 11. Two conchs are pictured on a sand flat near the fringing reef separating North Sound from the open sea.



Fig. 12. In many places near the lagoonward extremity of the sand flat calcareous green algae such as Penicillus live in the rather stable sand substrate.

Conical mounds of sand constructed by marine organisms, possibly by the burrowing shrimp Callianassa or the worm Arenicola, are common on the sand flat and continue to occur as the sand apron grades into the grassy meadows of North Sound's interior.

Rock Floor

Between the moat and the lime muds of North Sound's interior is a band of exposed rock floor or hard grounds which parallel the present-day fringing reef (Fig. 13). This relatively sediment-free area is topographically higher than adjacent areas. It forms a slight barrier between the living reef and the interior of North Sound.

The organic community colonizing this submarine ridge is typical of most exposed, rocky substrates. Alcyonarians and a spectrum of brown algae are most characteristic. An impoverished scleractinian fauna, consisting mainly of Diploria clivosa and Siderastrea radians, is present. Millepora alcicornis is present but usually is limited to finger-like encrustations of alcyonarians. Other encrusting organisms relatively common to the rocky floor are coralline algae and the yellow-brown boring sponge, Cliona. Black, long-spined echinoids, Diadema, are especially numerous in the irregular rocky areas. Where sand thinly veneers the rock floor, a sparse growth of green algae, vascular marine plants, and loggerhead sponges results.



Fig. 13. Many small patch reefs and other forms of hard grounds protrude through the sediment cover as rock floor areas of the sound. These regions are usually colonized by alcyonarians and small corals.

Moat

At the shoreward limit of the rubble flat sand progressively replaces boulders and cobbles. The bottom profile at this point drops rather abruptly, forming a channel-like feature. This depression parallels the reef trend and gradually shallows shoreward. The width of the moat zone is variable, and water depths range from approximately 2 to 5 m. The bottom is either a current-swept rock surface or a thin veneer of sand, usually ripple marked. Algae-encrusted coral rubble, derived from collapsed colonies of Acropora cervicornis, is present in localized areas. The density of living coral appears to vary inversely with the occurrence of sand on the bottom.

The moat community can be characterized by Montastrea annularis, A. cervicornis, and alcyonarians (Figs. 14 and 15). Hemispherical and donut-shaped heads of M. annularis, up to approximately 3 m in diameter, form the nucleus for patch reefs. Smaller and less important corals associated with these large heads include Agaricia agaricites, A. nobilis, Dendrogyra cylindrus, Diploria labyrinthiformis, D. strigosa, Eusmilia fastigiata, Porites astreoides, P. furcata, P. porites, and Siderastrea siderea. Alcyonarians and colonies of delicately branching A. cervicornis inhabit areas between patch reefs. Locally, A. cervicornis is concentrated into thickets, and its greatest density is shoreward of that of M. annularis.

A sparse growth of green algae covers the stabilized sand areas among the patch reefs, coral thickets, and on the sandy shoreward flank of the moat. Halimeda is the most common green alga associated with the corals. Penicillus joins Halimeda in being the most abundant calcareous green alga in the stabilized sand areas.



Fig. 14. Patch reefs of Montastrea annularis are common in the moat environment.



Fig. 15. In addition to the Montastrea annularis colonies which can be seen in the background, Acropora cervicornis is a very common moat zone coral.

Rubble Flat

Topographically, the rubble flat slopes very gently shoreward from the reef crest and is covered by shallow water over its entire extent. It is formed almost exclusively of boulder- and cobble-sized pieces of Acropora palmata which have been extensively bored and encrusted by marine organisms (Fig. 16). However, when compared to the lush coral fauna of the reef crest, this environment appears very sparsely populated.

Encrusting organisms include calcareous red algae, the Foraminifera, Homotrema rubra, serpulids, Bryozoa, Millepora alcicornis, and others. Small clumps of Padina and other brown algae are common. The abundance of these algae gives the rubble flat an overall brown appearance. Green algae are present, but in limited varieties and numbers.

Alcyonarians, bladed M. alcicornis, and a few scattered coral heads comprise the largest faunal elements. The most common corals on the rubble flat are Diploria clivosa, Porites astreoides, Siderastrea radians, and S. siderea.

As an accessory organism, the long-spined echinoid, Diadema sp., is very abundant among the coarse debris of the rubble flat.

Reef Crest

The fringing reef which separates North Sound from the open sea is a submarine ridge intermittently broken by channels. At low tide the highest points on this ridge are exposed. Its rather flat crest is colonized by a flourishing growth of corals and more subordinate



Fig. 16. Tossed colonies of the common reef crest coral, Acropora palmata, are regularly found on the rubble flat. These colonies are broken and transported lagoonward during storms.

forms of benthonic marine life. It is the culmination of two oppositely sloping surfaces, a seaward-dipping rock surface in the fore-reef and a shoreward-dipping debris plane in the back reef. Although all the fringing reefs of Grand Cayman exhibit very similar submarine topography, the reefs of North Sound support the most luxuriant reef crest coral community.

The most abundant, and structurally the most important, coral at the reef crest is the large, branching Acropora palmata (Fig. 17). It clearly is the dominant form of marine life in the reef crest community. A preferential orientation of the tree-like colonies occurs with fronds extending toward prevailing seas. Symmetrical, flower-like colonies occur in the more protected shoreward areas of the reef crest. The fronds and trunks of these colonies are thin, whereas those taking the full force of the surf tend to be more massive. A. palmata gives the area an irregular, comb-like appearance, the teeth extending seaward.

Other corals occur at the reef crest but are distinctly less abundant than A. palmata. Heads of Diploria strigosa, D. clivosa, and Montastrea annularis, up to several feet in diameter, are common between the colonies of A. palmata. These subordinate corals can be found throughout the reef crest but appear to be more concentrated shoreward of the greatest concentration of A. palmata. Smaller corals, Agaricia agaricites, A. nobilis, Porites porites, and P. astreoides, find suitable ecologic niches under and between the larger corals.

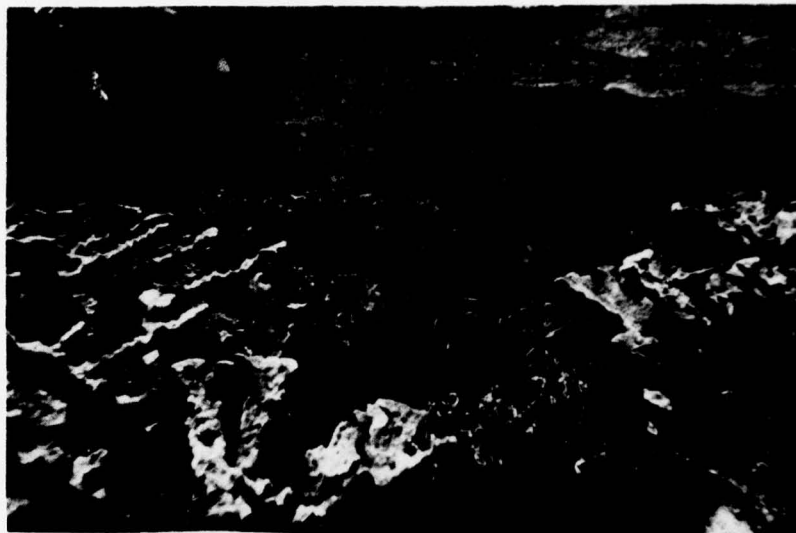


Fig. 17. Acropora palmata is the most prolific coral at the reef crest. A high population density of corals is characteristic of this environment.

The hydrozoan Millepora alcicornis occurs both in bladed and encrusting forms (Fig. 18). Like A. palmata, it can withstand a very high-energy environment. In areas where A. palmata is missing from the reef crest community, probably because it has been destroyed by storms, bladed M. alcicornis becomes very abundant. Encrusting M. alcicornis usually occurs on alcyonarians.

Halimeda is rather inconspicuous but is present at the reef crest. An abundance of the long-spined echinoid Diadema sp., along with many other small varieties of benthonic life, occur in ecologic niches provided by the larger and more noteworthy members of the environment.

Encrusting Foraminifera, especially Homotrema rubra, and coralline algae cover the bases of coral colonies and debris trapped in the structural framework of the reef. Algal coatings are not restricted to the reef crest but extend shoreward on a rubble-covered plane built by wave-tossed debris from the reef crest.

Fore-Reef Shelf

The fore-reef shelf may be divided into two terraces. An abrupt break in slope occurs at approximately 8 m, which delineates the seaward extent of the upper terrace. The lower terrace margin is at approximately 21 m, where the fore-reef shelf is intersected by an extremely steep fore-reef slope plunging off into very deep water. Both terraces persist on the narrow shelf around the entire island and are presumed to be related to eustatic sea level changes.



Fig. 18. Bladed Millepora alcicornis is an important member of the reef crest community. Millepora takes over the reef crest in many places where corals have been eliminated by storms.

Upper Fore-Reef Terrace

The upper or shallow terrace is characteristically a seaward-dipping rock surface (commonly dissected by shallow grooves) and is only sparsely populated by colonies of carbonate-secreting organisms (Figs. 19 and 20). This comparatively barren plain is perpetuated with slight variations on all sides of the island and under considerably different energy conditions. Grooves trend normal to the shoreline or fringing reef alignment, depending on the shoreward limit of the upper terrace. Where best developed, grooves are steep sided and floored by a thin veneer of sediment which is generally medium- to coarse-grained. With the exception of the seven-mile beach area on the island's lee side, most sediment on the upper terrace is concentrated in grooves. Mats of filamentous brown algae, which reside on the hard substrate surfaces, do, however, trap a thin layer of particulate carbonate material.

The coral community of the upper terrace is dominated by Acropora palmata in the shallow areas, where the upper terrace slope terminates landward at a shallow fringing reef crest. These massive branched colonies extend only to depths of approximately 4.5 m. Most of the terrace surface is inhabited by alcyonarians, gorgonians, encrusting and small hemispherical coral colonies, and filamentous and other forms of brown algae. Apparently, the abundance of flexible and encrusting or low-lying growth forms is in response to the intense expenditure of wave energy across this zone. High energy growth forms give way to more diverse reef communities (at the leading edge of the upper terrace)

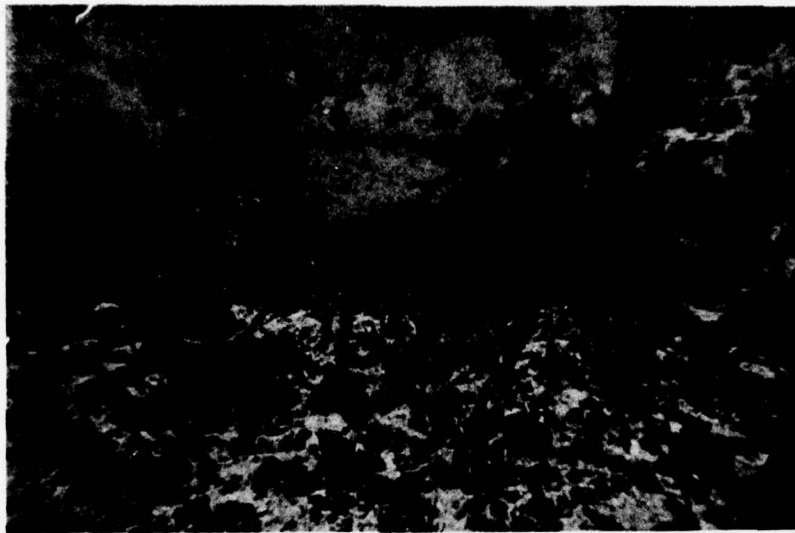


Fig. 19. Seaward margin of the shallow fore-reef shelf (approximately 8 m). In many areas corals become abundant at this position on the shelf.

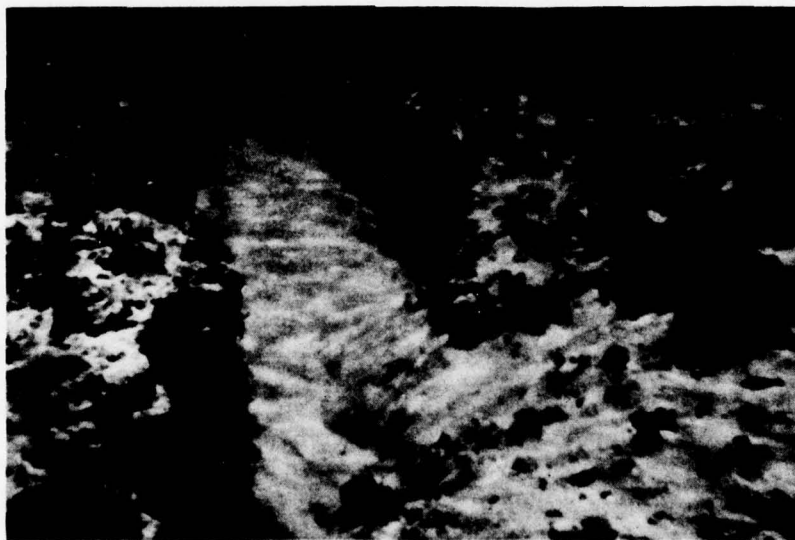


Fig. 20. Shallow steep-sided groove on the shallow fore-reef shelf. Note the sparse coral growth in this region (depth 3 m).

where conditions are most quiescent. Reef morphology is quite variable in this transition zone between the upper and lower terraces depending upon position around the island and, hence, energy climate. Coral colonies, Montastrea annularis, M. cavernosa, Diploria strigosa, D. labyrinthiformis, Agaricia agaricites, Dichocoenia stokesii, and others combine to produce a remarkable buttress development at the upper terrace margin along high energy portions of the coast. In most cases, the buttresses represent the distal ends of actively growing coral spurs which extend down to the lower terrace level. Reef mounds, the foundations of which are M. annularis, also develop on this area of the shelf and sometimes grow to within 4.5 m of the surface where A. palmata may colonize.

Lower Fore-Reef Terrace

The lower fore-reef terrace may be subdivided into three parts: (1) sediment plain, (2) coral spurs, and (3) deep reef.

The sediment plain comprises the landward portion and is composed of extremely coarse biogenic carbonate material (cobbles, pebbles, and coarse sand) near the buttresses of the upper terrace (Fig. 21). Grain size diminishes seaward and can be predominately in the silt-clay range where large expanses of sediment have developed. The thickness of sediments on this area of the shelf is still unknown for Grand Cayman. Sediments from a similar environment in Jamaica, however, have been found up to 27 m thick.

Colonization of organisms on the sediment surface is minimal. They are restricted to a few forms of calcareous green algae, Halimeda being the most abundant, and hard substrate forms, corals, and alcyonarians, where large clasts offer a firm surface on which to attach. An abundant infauna is present. Mounding of sediment, predominately by marine worms, is common where a broad sediment plain has developed.

Spurs of living coral extend landward from the seaward margin of the lower terrace. These features are clearly constructional and are separated by narrow, sand-filled grooves where colonization of reef-building organisms is made difficult by an instable substrate. Orientation of the spurs is normal to the shelf margin, which generally parallels the shoreline. Detached spurs, surrounded by sediments which do not intersect the shelf edge, assume a teardrop shape with a long axis orientation coincident with larger scale features (perpendicular to shelf margin). Dominant coral growth on the spurs can be attributed to Acropora cervicornis and Agaricia agaricites, the former of which is an extremely prolific sediment producer (Fig. 22). Many other corals flourish in this environment, including multiple species of Montastrea, Diploria, and Porites. Volumetrically, less important genera are represented by Colpophyllia, Eusmilia, Isophyllia, Meandrina, Mussa, and Mycetophyllia. Living within the coral-dominated communities are a host of other organisms including many varieties of sponges and alcyonarians. Although these and other organisms are vital to the maintenance of a healthy reef ecosystem, many of them may be relatively unimportant as contributors to the reef structure. Noted exceptions are the coralline red algae which function as the most important reef-binder organisms.



Fig. 21A. Burrowed and rippled sediment on the lower fore-reef shelf (depth approximately 18 m).

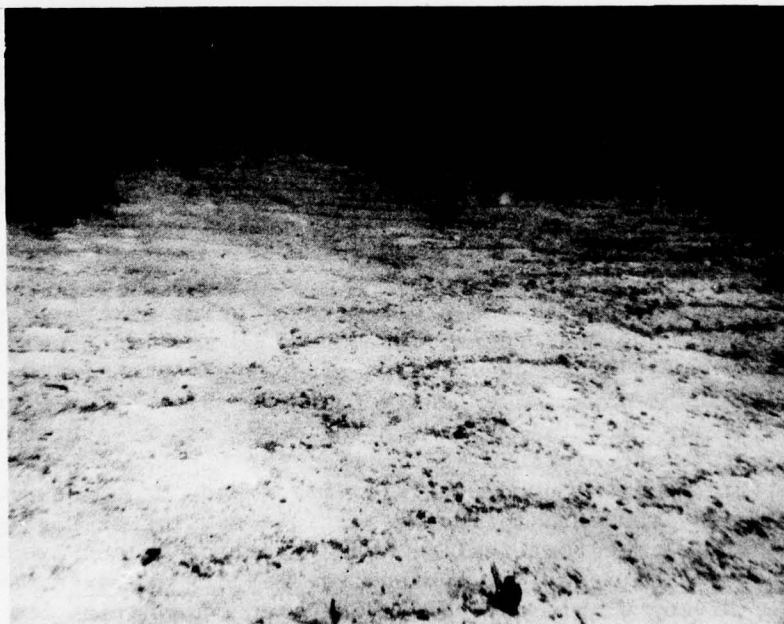


Fig. 21B. Diverse coral community on the coral spurs of the lower fore-reef shelf (depth approximately 20 m).



Fig. 22. Acropora cervicornis is an abundant member of the coral community that inhabits the coral spurs of the lower fore-reef shelf (depth approximately 16 m).

They not only help weld the corals into a solid reef framework, but also are responsible for stabilizing sediment caught in the reef matrix. Sediment is primarily derived from physical and biological degradation of corals and the green calcareous alga Halimeda. Halimeda grows prolifically among the other reef organisms.

The deep reef occurs at the seaward edge of the lower terrace where an abrupt break in slope marks the beginning of the fore-reef slope. Here, at the shelf margin, coral spurs terminate in a ridge paralleling the shelf edge. This ridge is intermittently dissected by narrow, sand-filled grooves. The degree to which the deep reef morphology is amplified appears to depend on the energy climate under which it developed. Where energy conditions are the highest, remarkable buttresses of living coral protrude into deeper water (Fig. 23). These huge coral spurs commonly coalesce, forming a wide variety of tunnel and cavern structures. The massive buttresses create overhangs and vertical cliffs facing very deep water and have as much as 20 m of relief. Reefs at comparable depths, but exposed to considerably less energy, exhibit abrupt seaward slopes but much less exaggerated buttress formation. The corals most responsible for the construction of these features are Montastrea, Agaricia, and Diploria. With the exception of the buttress tops, coral growth forms are shingle-like. The plate-like geometry allows corals to optimize their light gathering capability. Algae, zooxanthallae, which reside in the coral tissue aid in the calcification process and require light for photosynthesis. Halimeda is abundant and a very important sediment producer at deep reef depths.



Fig. 23. Large coral buttresses are common at the shelf edge. Narrow sediment-floored grooves act as conduits for moving sediment off the shelf and into deep water environments (depth approximately 22 m).

Fore-Reef Slope

Little is known about the fore-reef slope of Grand Cayman Island below water depths of 60 m. However, it appears that this subdivision is structurally and biologically well defined. The steepness of the upper slope varies with intensity of energy climate, which is also the case with the development of the deep reef. The upper portions of the slope exhibit gradients that range from vertical cliffs to approximately 50° to vertical. Sediments are introduced to the fore-reef slope by narrow grooves through the deep reef. In areas where deep reef morphology is exaggerated, evidence of large-scale slumps is often visible. Overhanging reef lobes grow to the point of structural instability and shear off into deep water.

The fore-reef slope has rich benthic communities dominated by calcareous algae, corals, Gorgonia, and sponges (Figs. 24 and 25). Plate-like growth forms are common among the corals, of which Montastrea and Agaricia are most abundant. Coarse sand is produced by an abundance of Halimeda, many species of which are characteristic of the environment. Other organisms producing a finer sediment are Foraminifera and Bryozoa. Most sediment on the fore-reef slope, however, is contributed by shallower environments.

Deep Island Slope

Recent research on the deep island slope environments (generally below 1,000 m) has confirmed the previous notions that large volumes of



Fig. 24. The fore-reef slope is inhabited by plate-like corals of Montastrea and Agaricia (depth approximately 45 m).



Fig. 25. Large sponges are common in deep fore-reef environments. The sponge in this picture is 1.5 m tall (depth approximately 45 m).

relatively shallow water sediment are being transported off the shelf. Figure 26 illustrates the nature of this sediment from a depth of approximately 2,000 m off the northern coast of Grand Cayman. This figure clearly illustrates the important contribution of shallow-water sediment at these depths. Thalassia blades, conch shells, and Halimeda flakes are common constituents of these sediments, all of which are derived from shallow-water regions of North Sound and its adjacent narrow fore-reef shelf. Large blocks of reef material, probably derived from the seaward margin of the fore-reef shelf as well as deeper reef environments, are found in abundance at depths of 1,000-2,000 m. Two submarine canyons that seem to emanate from the two main passes in the North Sound reef appear to function as preferential conduits for moving shallow sediments into deep depositional environments. The mechanisms of off-shelf sediment flux and downslope transport are still somewhat problematical.

BOULDER RAMPARTS

It has been shown by many studies that extensive geomorphic changes occur in carbonate environments as a result of violent storms; many landforms are destroyed and new features are developed. These catastrophic events produce significant biological and sedimentological changes as well. Boulder ridges or ramparts along many coasts of Grand Cayman can be attributed to such high energy processes.

Boulder ramparts are linear rubble accumulations that parallel the coast, but they may occur at various distances from the present

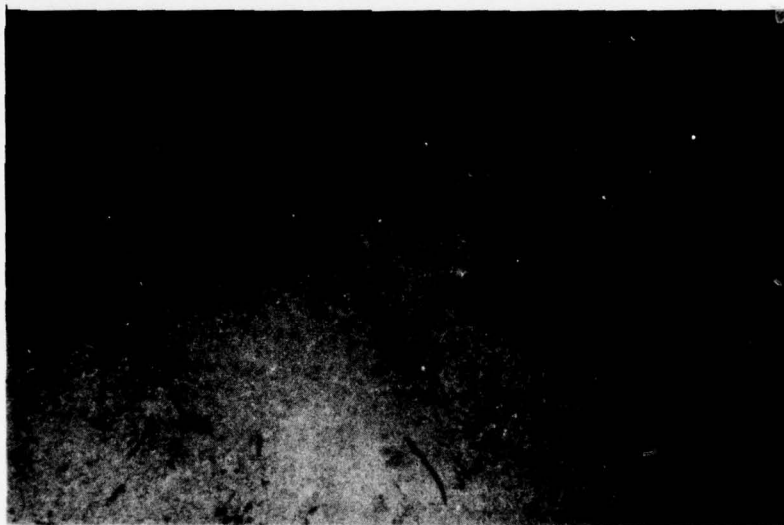


Fig. 26. Sediment surface as photographed at a depth of approximately 2,000 m off Rum Point Channel, along the northern coast of Grand Cayman Island. Note the elongated Thalassia blades and the conch shell (upper right), both of which were transported from shallow-water environments of North Sound. (Courtesy of C. H. Moore, Jr.)

shoreline (Fig. 27). They exist along practically all coasts of Grand Cayman but are especially well developed on the southern and northeastern sides of the island (Fig. 28). Ranging in height from approximately 2.5 to 5.5 m and in width from 15 to 60 m, the ridges are most distinct along coasts where there is no fringing reef and where the Ironshore is only a few meters above sea level. Where steep bluffs meet the sea or where fringing reefs act as a buffer to storm waves, boulder ramparts do not develop. Storm berms, composed mostly of sand mixed with cobble- and boulder-sized material, are common in the latter case.

Coral fragments, ranging from pebble to boulder sizes, are the principal constituents of the ramparts (Fig. 29). Sand-sized and finer particles are largely missing from these deposits; however, smaller sized sediments occur in various proportions as a matrix material. The coral fragments exhibit a rather "fresh" appearance, which suggests that transit time from growth areas was minimal. In a few areas, where boulder ramparts have been dissected, crude internal stratification is revealed. Some sections also show imbrication of large slabs of Ironshore and coral colonies, an indication that they have been transported landward.

Cayman's upper shelf terrace is rather devoid of coral growth except in areas where fringing reefs have developed. This situation presents a problem of source for most well-formed boulder ramparts. In addition, many of the constituent coral boulders are not indicative of shallow water. Underwater surveys, coupled with constituent particle



Fig. 27. Linear boulder rampart along the southern coast of Grand Cayman east of Frank Sound.

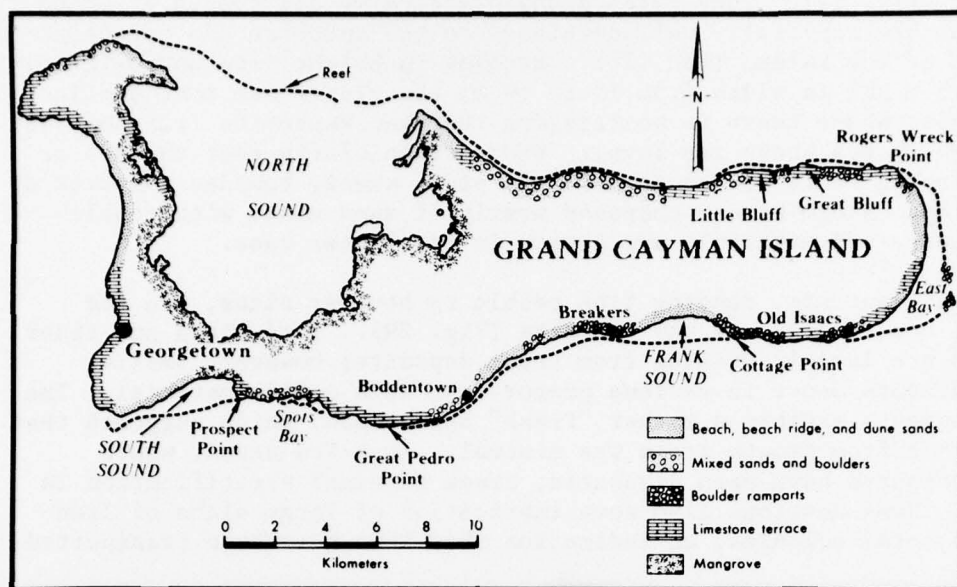


Fig. 28. Map of boulder ramparts and other landforms along the coast of Grand Cayman Island.



Fig. 29. Constituents of a boulder rampart along the south coast of Grand Cayman.

analyses of the boulder ridges, suggest a source area with water depths ranging between 6 and 10 m. This area of the shelf represents the seaward edge of the upper terrace, which generally supports a thriving and diverse coral community. Coral spurs, extending down to the lower terrace level, are heavily populated by scleractinia, representing both shallow and deep environments. The distal ends of spurs, which are sometimes within 6 m of the water surface, are generally inhabited by branching colonies of Acropora palmata, while sides are composed of hemispherical coral growth forms.

The constituents from a boulder rampart study site along the south coast were studied using a sample size of 500 selected on a randomized grid. Size analyses were also performed for several study areas. It was found that boulder ridges exhibit a sorting (σ) of 0.5 and mean size (M_z) of about -7 to -8 ϕ . Sorting of about 0.5 is also the range for beaches of Grand Cayman. Sedimentary deposits attributable to violent storms probably comprise a considerable proportion of the total sediment record in many places. Although it is possible that the boulder ramparts of Grand Cayman may not be geologically preserved, similar ridges in other settings are definitely being cemented and, in some cases, are aiding in the formation of new islands. McKee (1959) and Fairbridge and Teichert (1948) describe this island-forming and island-modifying process from several Pacific atolls.

INTERTIDAL CARBONATE CEMENTATION

Beach rock cementation on Grand Cayman (Fig. 30) occurs in the intertidal zone bounded by the mean high tide above and extending a



Fig. 30. Beach rock on the northwest coast of Grand Cayman.

considerable distance below mean low tide, indicating that beach rock cementation probably merges seaward with submarine cemented hard grounds. Dominant cement fabrics and mineralogies include bladed-equant magnesium calcite cement, aragonite needle crust cement, and magnesium calcite micrite crust cement. The ubiquitous, equidimensional cement crust fabric indicates a dominantly phreatic environment of formation (Fig. 31). The aragonite needle crust (Fig. 32) and clear, bladed-equant magnesium calcite crust were formed in intergranular pore spaces by either direct physical precipitation or secondarily as a by-product of biologic activity. This contention is confirmed by their well developed crystal habits. Micritic cements, on the contrary, commonly show the direct effects of biological activity (Fig. 33). Thin-section and scanning electron microscope analyses of these cement types regularly produce evidence of algal and fungal filaments as well as other organic structures.

The beach interstitial water systems at Grand Cayman appear to be primarily of mixed meteoric-marine origin with high Sr to Ca ratios and low Mg to Ca ratios. Cement chemistry, regardless of morphology and mineralogy, including stable isotopes, reflects these chemical variations. This trend strongly suggests that Grand Cayman beach rock cementation has in the past and is currently taking place rapidly and simultaneously across relatively broad areas of the beach under intertidal mixed meteoric-marine conditions.

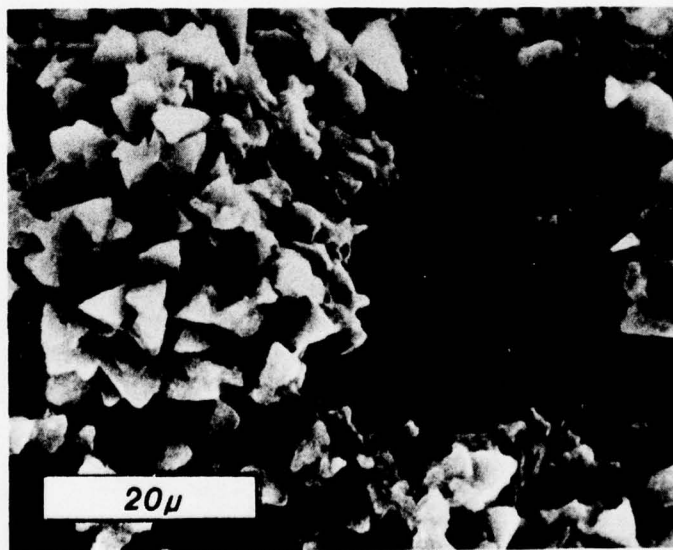


Fig. 31. SEM photomicrograph of a beach rock cement showing a bladed-equant crust. Note well developed steep rhombohedral crystallites (courtesy of C. H. Moore, Jr.).



Fig. 32A. General view of an aragonite needle crust cement at the junction of 3 grains. Note the clarity of the needles and development of micrite rims on each grain.



Fig. 32B. SEM photomicrograph of aragonite needles showing well-formed crystals (courtesy of C. H. Moore, Jr.).

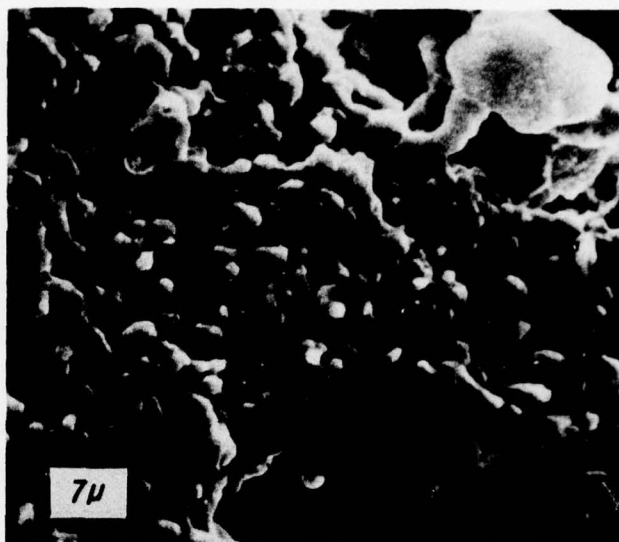


Fig. 33. SEM photomicrograph of the surface of a dense micrite intergranular crust. The large globular bodies are probably of biologic origin (courtesy of C. H. Moore, Jr.).

PLEISTOCENE CARBONATES OF GRAND CAYMAN

In addition to a variety of unconsolidated Holocene carbonate sediments, Grand Cayman also provides an opportunity to study ancient limestones which are representative of many depositional environments. The Pleistocene limestones are especially interesting, because they are partially lithified equivalents of sediments now being formed by modern environments. Constituent particles and in situ skeletal remains from many of the Pleistocene deposits are identical to those forming today.

The Pleistocene carbonates of Grand Cayman have been grouped into the Ironshore formation by Matley (1926). This relatively young limestone forms an emergent coastal terrace of low relief which has accreted around the older Bluff limestone and now occupies a sizeable portion of the island periphery. Some of the best exposures of Ironshore are on the lee side of the island. Special attention will be given to exposures along the southwest coast near Georgetown and the western margin of North Sound.

Depositional facies represented by the Ironshore formation include: shallow shelf, reef, back-reef, lagoon, oolite bar, and beach. Bulk mineralogy of samples from the Ironshore formation illustrates that processes of diagenesis have incompletely altered the original mineralogy of these carbonate deposits. High-Mg calcite, which is the least stable common carbonate mineral phase under freshwater conditions, has been almost totally removed. Although the original sediments probably contained as much as 50% high-Mg calcite in some environments, this phase is usually not detectable from bulk x-ray diffraction analyses.

Aragonite, which is intermediate between high-Mg and low-Mg calcite in the stability series, is still rather abundant. Thin-section analyses show, however, that in particular environments much of the original aragonite has been lost through solution and replaced by low-Mg calcite. Low-Mg calcite is the stable phase under freshwater conditions and, therefore, accounts for over half of the bulk mineralogy of Pleistocene samples thus far analyzed. Fabrics and cements suggest that the significant diagenetic alterations in Grand Cayman's Pleistocene limestones have occurred in the vadose zone. Such features as keystone vugs, moldic porosity, and meniscus and other cement types are commonly found which strongly suggest formation in the vadose zone. In addition to aragonite and low-Mg calcite, dolomite, which is common in the Bluff limestone, is sometimes found associated with the Pleistocene Ironshore.

During the field trip a stop will be made on an outcrop between Governor's Creek and Salt Creek along the western shore of North Sound. At this locality a Pleistocene tidal channel in the Ironshore formation will be examined (Fig. 34). Oolitic accretion beds have infilled the channel which has large clasts of lithified material at its base. A highly burrowed unit with many burrows prominently displayed on the outcrop occurs beneath the tidal channel fill.

One interesting area of Ironshore exposure along the southwestern coast of Grand Cayman contains large reworked slabs of oolitic lime grainstone beach rock. These Pleistocene deposits are in the form of extensive breccias which are incorporated in and are overlying reef flat and back-reef lagoonal deposits (Fig. 35). The lime grainstone breccias, however, contain typical meteoric vadose cement morphologies and distributional patterns indicating that they originated in the meteoric vadose zone, inland from the beach intertidal, and were transported to their site of deposition in the marine (probably back-reef lagoon) by major storm activity. The storm or storms apparently eroded the back-reef beach-dune shoreline exposing the horizons which were lithified in the meteoric vadose environment. This process initiated collapse of these horizons, immersion in saltwater, and possible transport into the adjacent lagoon. A schematic diagram of these basic events is presented in Fig. 36.

The surface of the Ironshore is generally weathered into an intricate, small-scale karst composed of jagged pinnacles, except in areas where the limestone is capped by a well-indurated carbonate crust. The karst development is also common of the Bluff limestone. It was determined that the lacy weathering patterns were the result of something more than simple rainfall and sea spray solution processes. Endolithic boring algae were found to be dominant agents in small-scale karst development. The term "phytokarst" has been applied to this type of limestone surface condition.

PHYTOKARST

An intricate, small-scale karst occurs along the coasts and elsewhere on Grand Cayman. This phenomenon can be found on the Pleistocene Ironshore and Tertiary Bluff formations. These brilliant white limestones



Fig. 34A. General view of Pleistocene tidal channel infilled with oolitic accretion beds.



Fig. 34B. Large clasts of lithified material occur in the channel base.



Fig. 35. General view of collapsed slabs of Pleistocene oolitic lime grainstone overlying back-reef sediments.

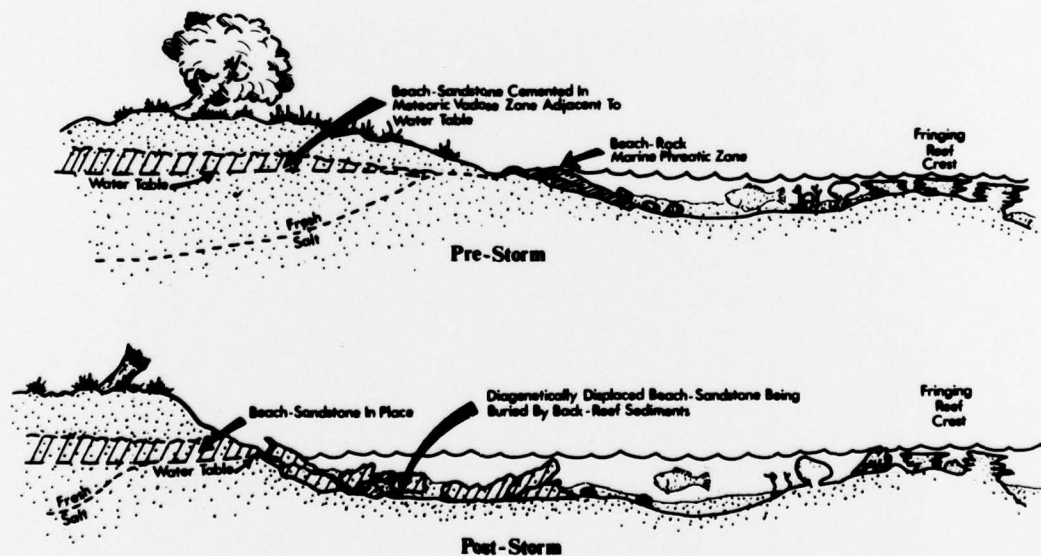


Fig. 36. Hypothetical cross-sectional reconstruction of the shoreline during Pleistocene times: (a) pre-storm, (b) post-storm (courtesy of C. H. Moore, Jr. and R. L. Folk).

have black surfaces which are intricately weathered into lacy and spongy patterns, leaving jagged pinnacles, over 2 m high at the town of Hell, riddled with randomly oriented holes having very sharp edges (Fig. 37). This karst differs from ordinary rainfall solution karst, also found on Grand Cayman, in four ways:

1. Hell-type karst is much more intricately dissected.
2. Hell karst has a black surface, while normal solution karst is whitish.
3. Ordinary solution karst shows definite gravitation at orientation of flutes, resulting from rainwater seeping down the slopes, while Hell karst is gravitationally unoriented - for detached pieces, it is impossible to tell proper orientation.
4. A penetration rind of endolithic algae characterizes and produces Hell karst, hence the designation "phytokarst."

Algal filaments, 10 microns thick, penetrate the limestone to a depth of 0.1-0.2 mm (Fig. 38). The surface is covered with black moribund algae, but filaments just beneath the surface are green and alive. Algae are the main agents of phytokarst sculpture, as evidenced by the lack of gravitational orientation (they can colonize and destroy any surface) and the fact that phytokarst is algally-coated. Normal solution karst is virtually algae-free. The surface algae can be removed from karsted limestones by burning or by soil and sediment cover, which results in white phytokarst. Gradations occur between solution and phytokarst, but end members are the most common (Folk et al., 1973).



Fig. 37. General view of extreme development of phytokarst near the town of Hell, Grand Cayman Island.

CARBONATE CRUSTS

Laminated limestone crusts found in ancient rock sequences are generally identified as marine algal stromatolites and used as indicators of an intertidal environment. Although examples of modern littoral algal mats are commonly cited in literature dealing with recent carbonates, indurated limestone crusts from tropical and subtropical environments have many algal mat characteristics, but may have had quite a different origin. Investigations by Kornicker (1958) in the Bimini Islands and Multer and Hoffmeister (1968) in the Florida Keys tend to indicate that some well-laminated, algal-like crusts may have formed above the intertidal zone. Although the occurrence of these subaerial limestone crusts has been reported from many tropical areas of the world, their origin is still somewhat problematical.

Exposed limestone on Grand Cayman is, in many places, capped by a well-indurated carbonate crust which has been measured up to 8 cm thickness (Fig. 39). The crust is best developed on the irregular surface of the low-lying Ironshore limestone in areas bordering the western shore of North Sound. The underlying Ironshore is poorly cemented and locally called marl. The overlying crust is much harder and, therefore, protects the Ironshore from surface erosion.

The top of the crust forms a smooth undulating surface, usually over a bioclastic calcarenite. In some areas, the crust can be found over an oolitic limestone. Crusts over oolites are generally much thinner and less complex internally than in other outcrop areas.

Three general crust types have been recognized from Grand Cayman (Fig. 40): (1) porous laminated crusts, (2) dense laminated crusts, and (3) thin, non-laminated crusts.



Fig. 38. SEM photomicrograph of algal filaments which bore into limestone surfaces to produce the intricate phytokarst found on Grand Cayman Island. Algal filaments are about 5 microns thick.



Fig. 39. General view of the undulating surface of the carbonate crust which covers a very irregular surface of eroded Ironshore limestone.



Fig. 40. A typical example of a porous, laminated crust showing an unconformable surface within the laminae.

Laminated crusts are divided into two groups on the presence or absence of highly porous laminae composed primarily of minute calcium carbonate tubes and intervening voids (Fig. 41). These forms generally overlie bioclastic limestones. Thin, non-laminated crusts are usually associated with oolitic limestones.

The carbonate crusts of Grand Cayman have the following distinguishing characteristics: (1) Crusts are darker in color than the underlying limestone. Reddish brown to gray-brown is generally the color, while the underlying limestone is white to beige. (2) Laminae are variable in thickness and composed of finely-divided organic stains. (3) Grain inclusions within laminae are rare but generally biogenic when they occur. (4) Oolites are commonly incorporated in the non-laminated crusts. (5) Crusts are composed primarily of two components: a) a very fine-grained, low-Mg calcite and b) organics in the form of stains and very finely divided fragments. (6) Porous layers contain a plexus of calcareous tubes which represent carbonate replaced organic rootlets. Walls of the calcareous tubes are generally composed of fine-grained calcite (micrite to micro spar). (7) Some voids within the laminae suggest, by their shapes, an origin resulting from solution of aragonitic or high-Mg calcite grains. (8) Organic content of all crusts tested has been less than 5%.



Fig. 41. Thin-section photomicrograph of a porous carbonate crust showing one of the small root tubes with much of the root structure preserved by the cementation process.

Proposed Origin of Crusts

Processes which affect low-lying tropical environments where crusts are most common are numerous and complex. Extreme seasonal variation in rainfall, intense heat, fluctuations in the shallow groundwater table, changes in microbial activity, and decaying plant debris probably all play a part in the crust-forming process. To date, the most widely accepted theory concerning the formation of limestone crusts has been presented by Multer and Hoffmeister (1968). They propose a rather uniform mechanism for the origin of all crust types which is operative beneath and adjacent to a soil cover. Examination of soil samples and underlying indurated crusts reveals a close similarity of constituent particles. In very simplified forms, the origin of subaerial limestone crusts results from the dissolution of carbonate particles in the soil cover and precipitation of carbonate on top of bedrock by percolation of charge solutions draining through overlying soils. Therefore, the crust-forming mechanism is an aggrading process.

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